Computational Simulations for Stability and Control ~ BCA State-of-the-Art

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Outline of Presentation

- Navier-Stokes solvers and areas of applications
- CFD issues and challenges
- Summary/future works

The presentation will show some of our recent work in using the NASA-built Navier-Stokes solvers for various applications including airplane control surface effectiveness study, Reynolds number scaling, and high lift configuration analysis.

Navier-Stokes Solvers and Areas of applications

- CFL3D/TLNS3D (NASA Langley)
  - ~ Spoiler reversal study
  - ~ Outboard aileron effectiveness
  - ~ Stabilizer/elevator effectiveness
  - ~ High speed pitch characteristics with vortex generators
- OVERFLOW (NASA Ames/Langley)
  - ~ High lift configuration
  - ~ Slotted wing

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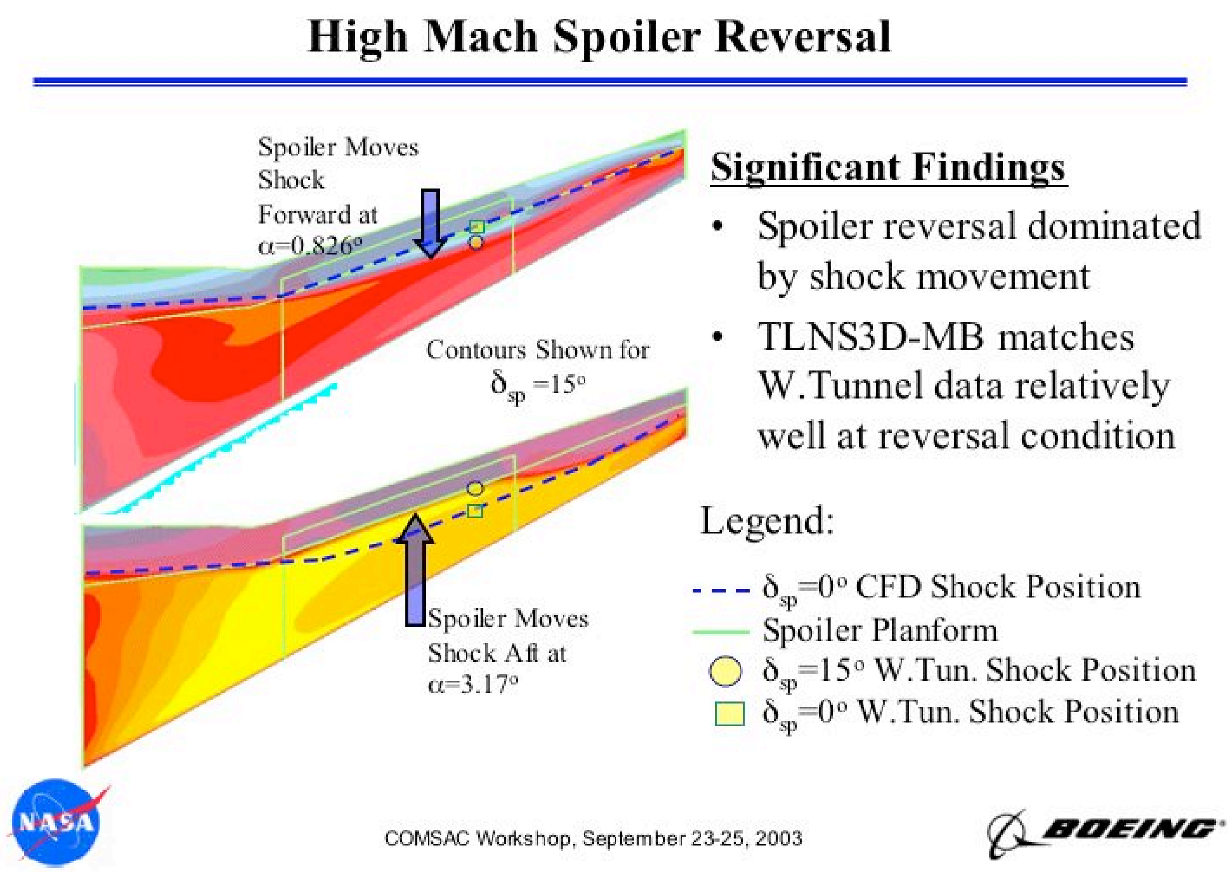
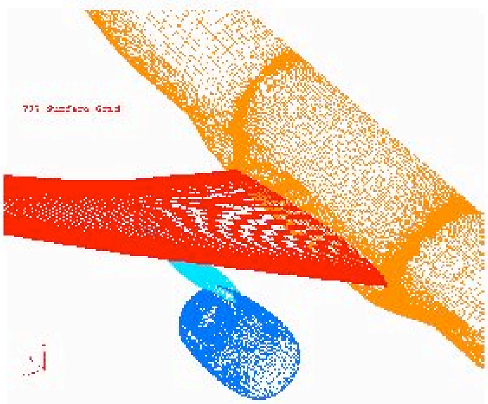
Our first application of Navier-Stokes technology to S&C problem is the use of TLNS3D code to predict the high speed spoiler reversal phenomenon. At high transonic Mach with given spoiler deflection, the wing lift decreases at low angle of attack, as expected. However, as alpha increases beyond a certain value, lift increases; a phenomenon known as spoiler reversal observed in the wind tunnel test. CFD not only gives correct prediction, it also provides flow field details which explain the cause of spoiler reversal.

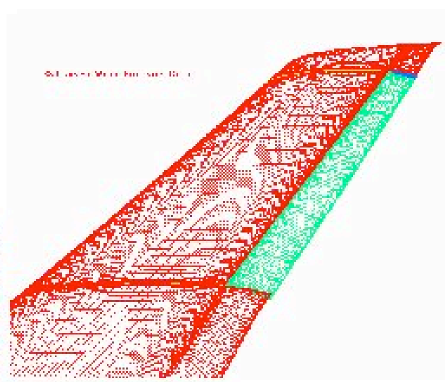


More recently, we have used both TLNS3D and CFL3D code to evaluate outboard aileron effectiveness with respect to Reynolds numbers. Multiblock grid approach was used to provide detailed representation of the geometry including aileron gaps. Both flow through and powered nacelles can be simulated in the analysis. Preliminary results show that effects of Reynolds number on aileron effectiveness were predicted correctly. More detailed study is in progress.

Twin Engine Configuration with Deflected Outboard Aileron

Wing/Body & Strut/Nacelle Model





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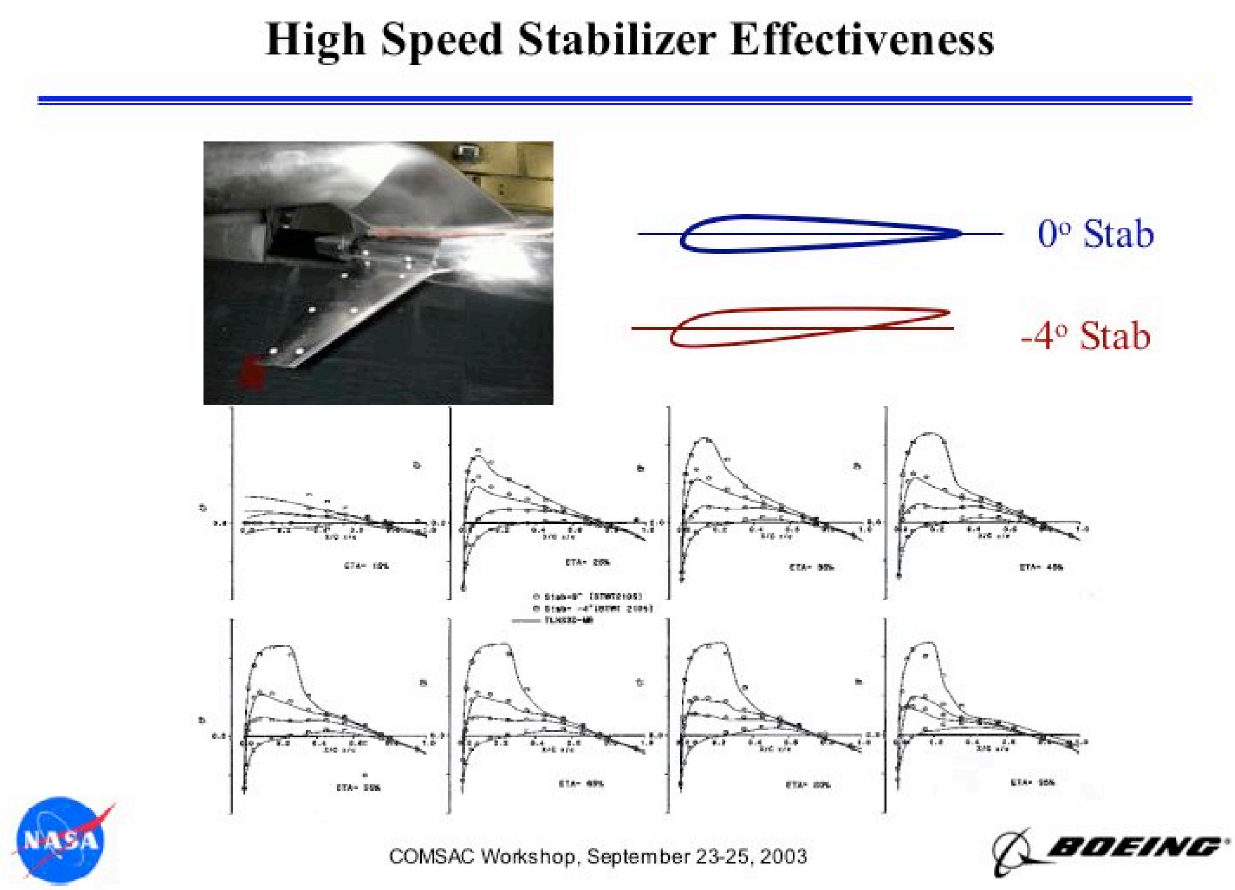
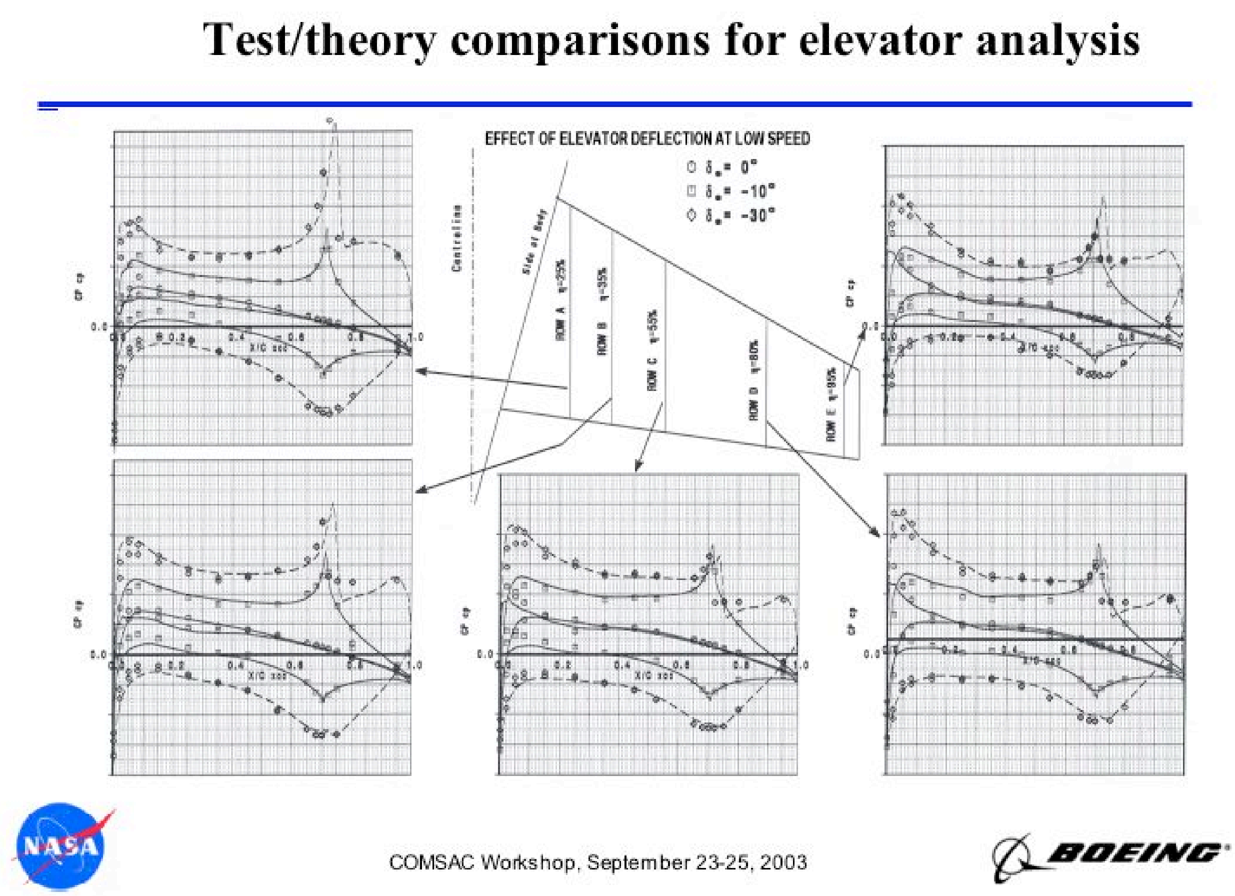
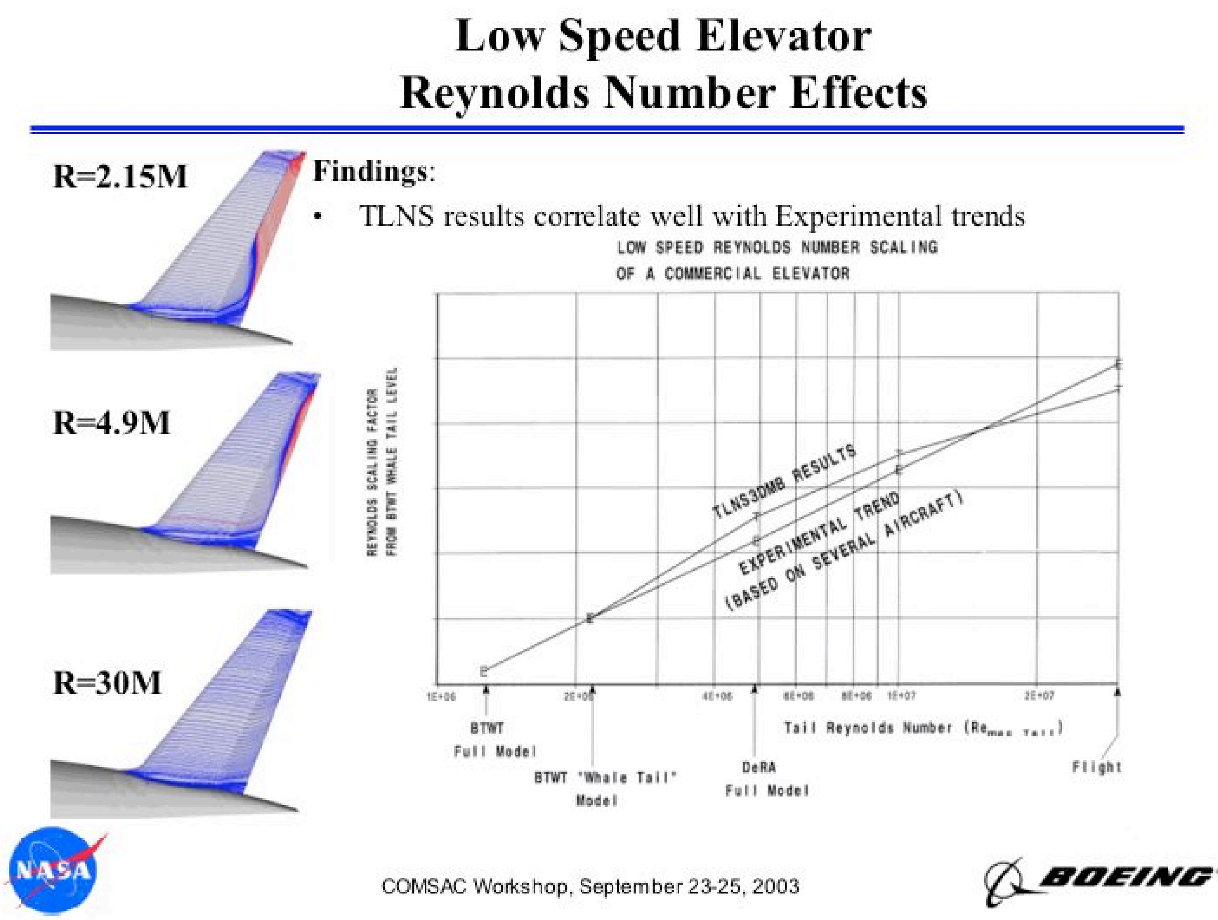
Applications of CFD for stabilizer or elevator effectiveness prediction are more challenging than the aileron analysis. One needs to resolve and capture the wakes generated by the wing, fuselage and nacelle, as they can affect the flow field in the horizontal tail region. With the use of denser grid in the wake regions and in the horizontal tail region, the CFD results correlate well with wind tunnel tail pressure data, and the tail lift slope curve also correlates with NTF data reasonably well.



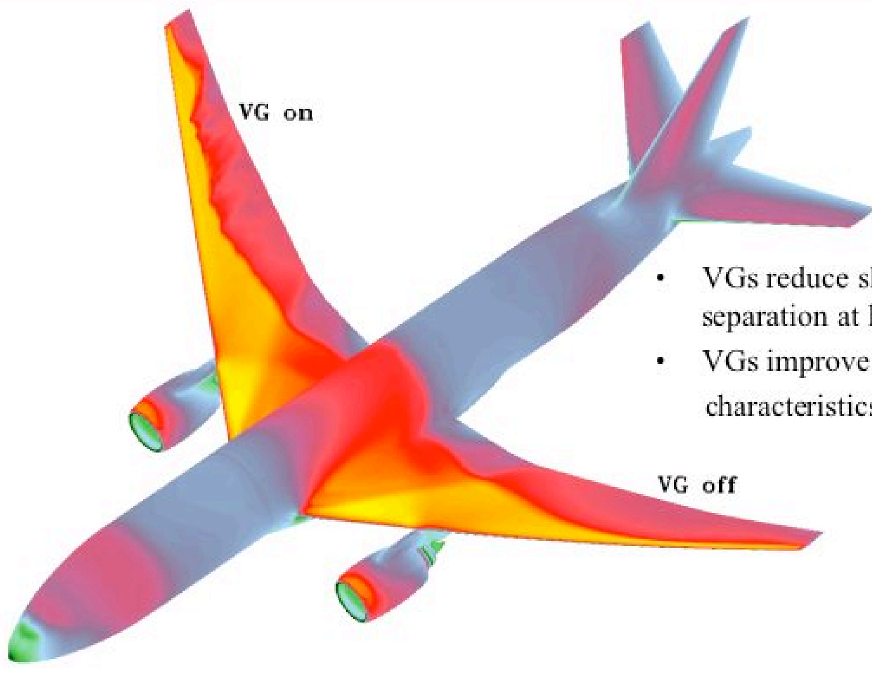
Similar analyses were carried out for elevator effectiveness prediction. Here the elevator deflection up to -30 deg. was analyzed. Even with fairly massive flow separation downstream of the elevator hinge line, the CFD analysis with Menter's two equation SST turbulence model provides good correlation with test data.



More extensive analyses were carried for low speed elevator Reynolds number effects. Boundary layer on the elevator becomes healthier at higher Reynolds number for a given elevator deflection. The flow separation downstream of the elevator hinge line at low Reynolds number reduces significantly at higher Reynolds number, and thus increases elevator effectiveness. The CFD prediction on elevator Reynolds number effects correlates reasonably well with the data.



Effects of Vortex Generators (VG) on Wing Pressures
at High Transonic Mach & High Alpha



- VGs reduce shock induced separation at high C_L
- VGs improve airplane pitch characteristics

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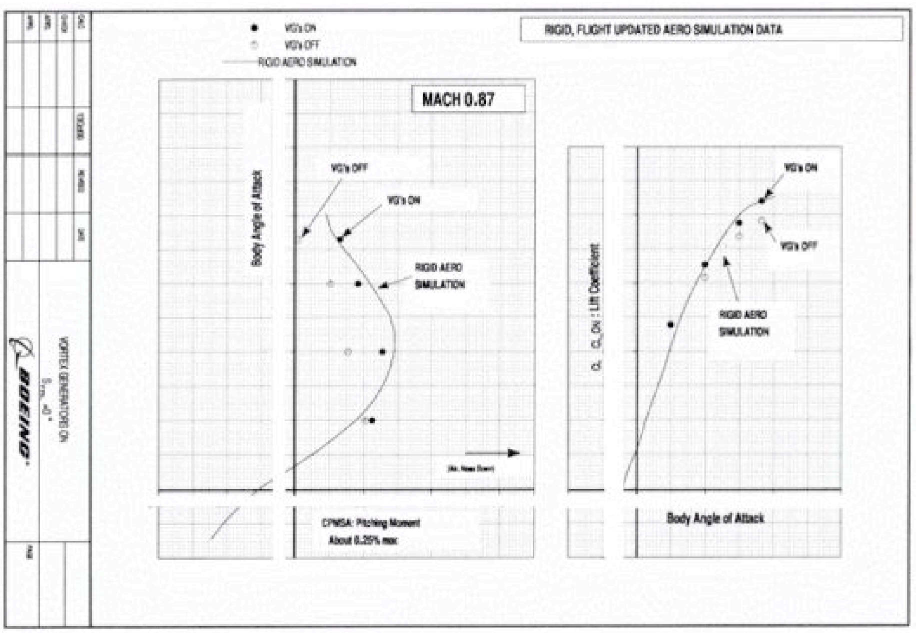
For structured, multiblock grid approach, the simulation of a cruise airplane configuration including all vortex generators on the upper surface of the wing is a significant challenge to both the grid generation and flow analysis tasks. To capture flow field details generated by the vortex generators, one must use fine grid in the vortex generator regions, and to capture and preserve the vortical flows downstream of the vortex generators, accurate Navier-Stokes solver with minimum numerical dissipation is needed. A patched grid system was used in the present study. Results showed that the effects of vortex generators on shock movement, and on airplane pitch characteristics were correctly predicted. The computing resources for this analysis are fairly reasonable, using 56 CPUs of an SGI Origin machine, one can get the solution of one flow condition (with 25 million grid points) within about 11 hour flow time.

VG Effects on Force & Moment Data at High Transonic Mach



ANALYSIS CASE

- Wing/ Body/ Nacelle/ Strut/ Tails + 16 VG's
- No Nacelle Chine
- Analyzed at flight condition (Cruise power)
- Flight Re

FINDINGS

- VG's effective at high alpha
- VG on results correlate well with flight test data

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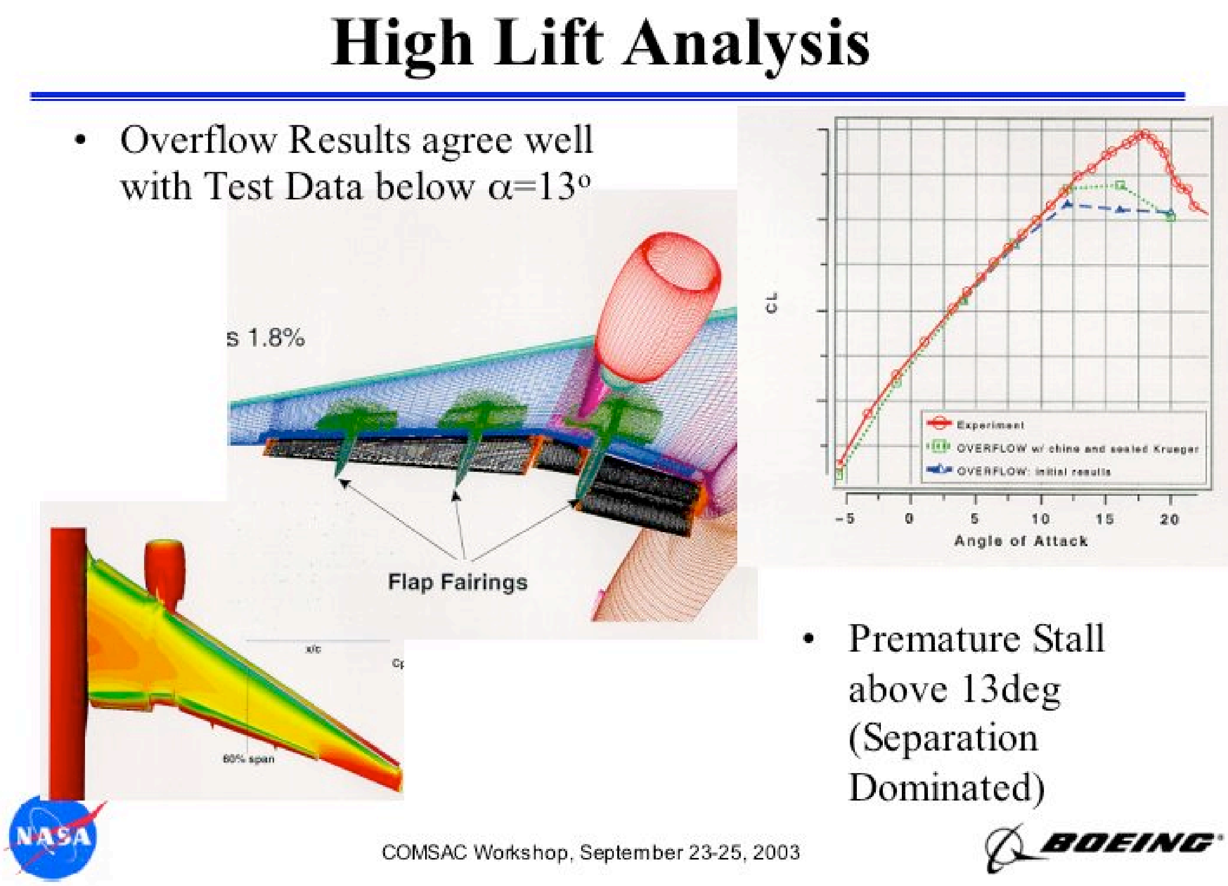
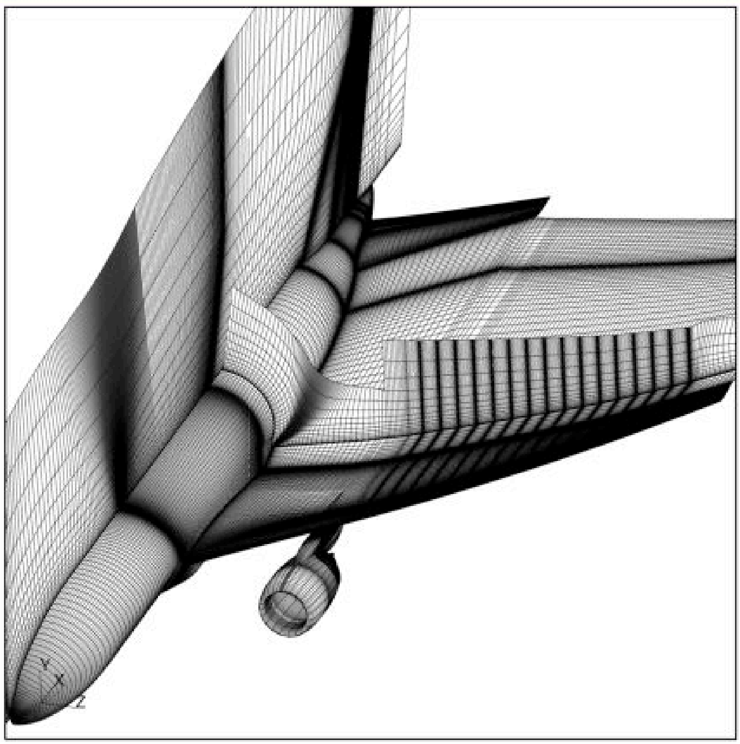
The most extensive use of OVERFLOW within Boeing Commercial Airplanes is the high lift analysis. Due to geometry complexity, overset grid is a preferred method for high lift predictions. At angle of attack lower than 13 deg., OVERFLOW results agreed quite well with test data. Above 13 deg., significant flow separation occurs on the flap elements, CFD results showed premature drop in lift. The causes of such discrepancy could be grid resolution, or turbulence model effects, which will be addressed in the later slide. More recently, OVERFLOW was also used heavily for high speed configuration analysis and design.



CFD Issues/Challenges

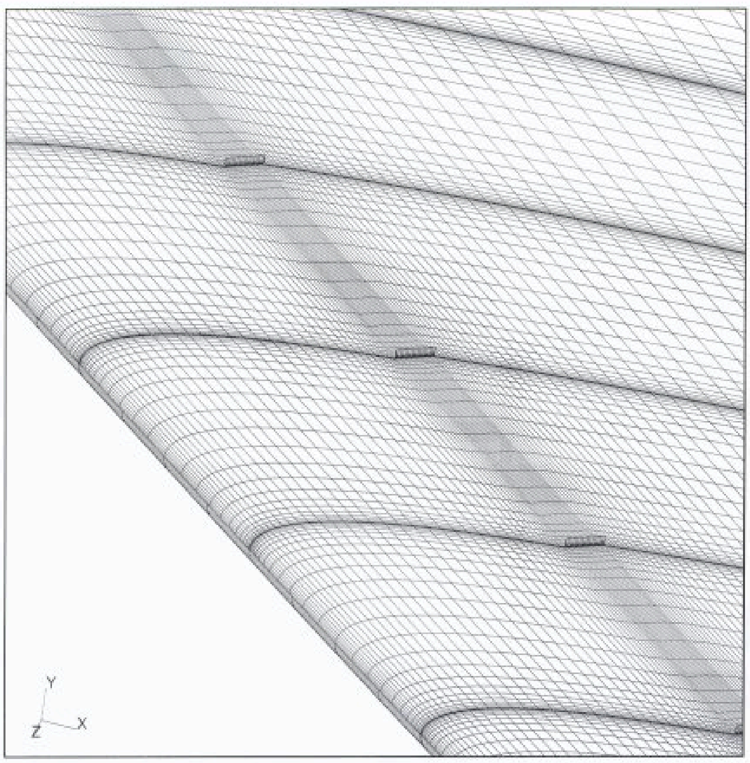
- Geometry/surface grid & flow field grid generation
- Turbulence modeling for separated flow
- Transition location, trip effects, wind tunnel wall (slotted) simulation
- Algorithm issues ~ accuracy, robustness, efficiency, etc.
- Large Caseload Capability
- Unsteady Flow, including dynamic derivatives

Geometry & Grid Generation –
Twin-Engine Airplane with Vortex Generators



For complex geometry analysis, grid generation is one of the most time consuming part of the analysis process. Grid spacing and grid quality affect numerical solution, especially for Navier-Stokes analysis. We have spent significant efforts in the past few years to develop both surface grid and flow field grid generation capability for either structured multiblock grid or overset grid. For the Navier-Stokes codes we are using at the present time, good quality grid is essential to get accurate and reliably converged solutions. The slides show the patched grid system used in the vortex generator simulation.

Geometry & Grid Generation –
Detailed Surface Grids near Vortex Generators



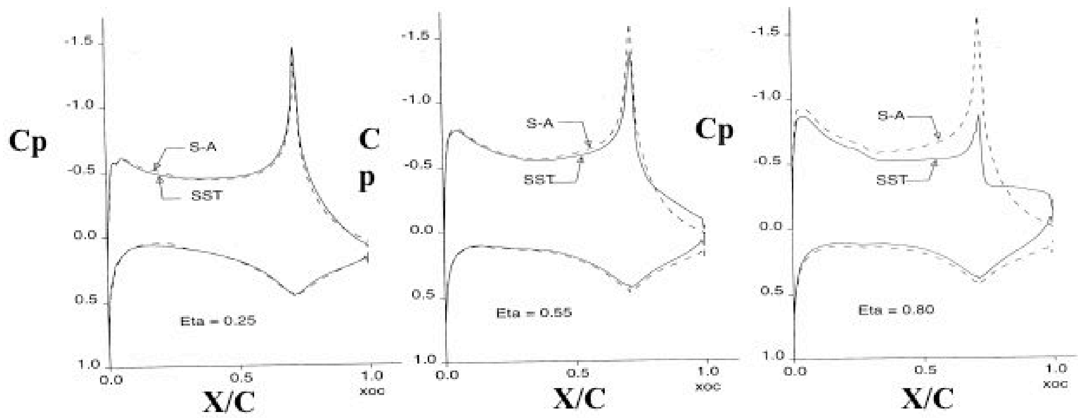
For cruise configuration analysis at near design conditions, most turbulence models can provide results which correlate well with test data. However, problems related to S&C or Loads applications usually have significant separations in the flow fields, where different turbulence models could give rather different results. The plots showed that at large elevator deflection (-30 deg.) where massive separation occurred downstream of elevator hinge line, the two-equation SST model provides more realistic results than the one-equation S-A model.

Turbulence Model Study

Menter's k-w SST vs Published SA

Findings:

- Minor differences for deflections of 0 and -10°
- Menter's model results in increased outboard separation at the -20°
  - Separation correlates with data better than SA model results
- Menter's model converges better at -30° deflection
- Menter's model used for the remainder of this study



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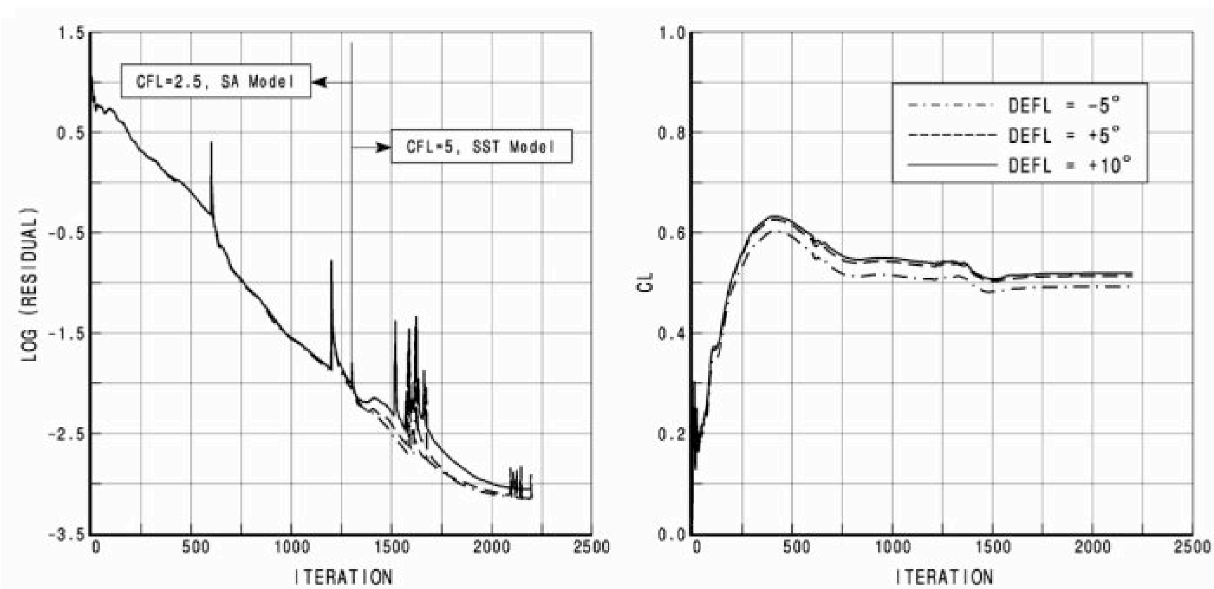
Transition, Slotted Wall Simulations, etc

- Boundary layer transition simulation ~ Essential for accurate viscous drag prediction, and for high lift analysis
- Slotted wall simulation ~ may be crucial for unsteady loads validation

Reliable convergence for N-S analysis is essential for S&C or Loads applications, where large number of cases are needed within a short period of time. The plots show typical convergence of CFL3D code at transonic speed. It requires many hundreds of multigrid cycles to converge the solution to acceptable level of numerical accuracy. For some cases, the convergence history could be worse, which deserve further research and improvement.

Algorithm Issues

Convergence History for a W/B/N/S with Deflected Aileron



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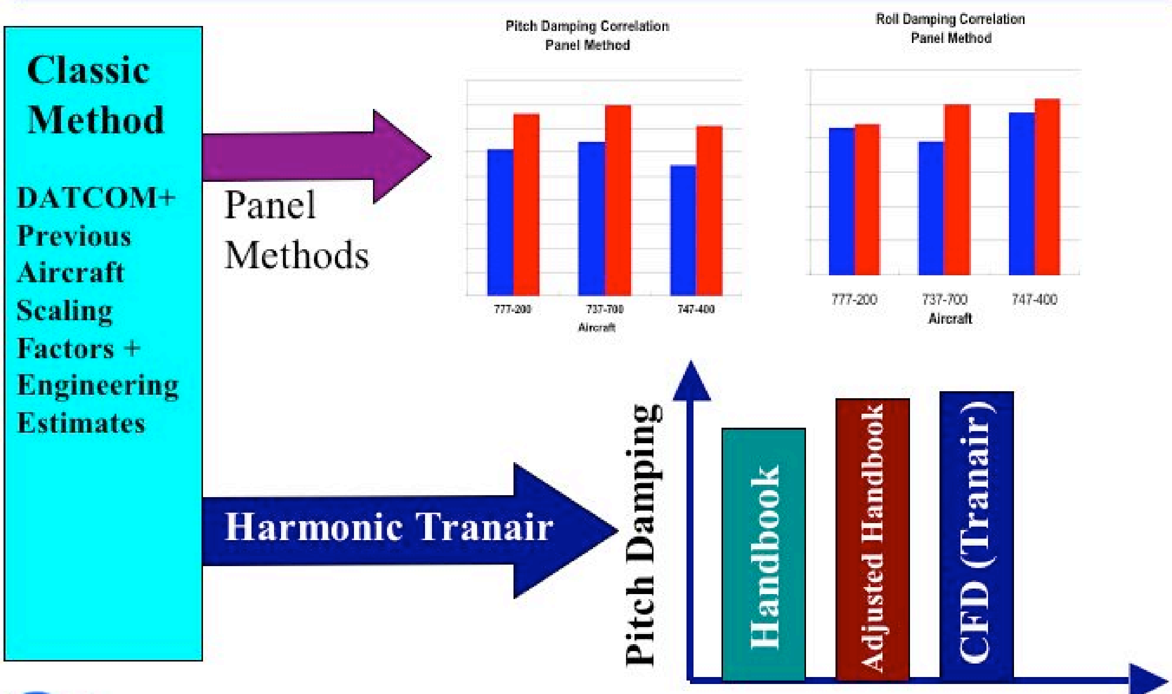
Large Caseload Capability

- Reynolds number scaling study
  ~ Problem size: 25 million grid points
- Wing control surface effectiveness study
  ~ Problem size: 30 to 65 million grid points
- Empennage analysis
  ~ Problem size: 10 to 15 million grid points
- High Lift Analysis
  ~ Problem size: 30-100 million cells

Each category needs hundreds of runs

Dynamic Derivative Prediction Methods



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Summary/Future Works

- Promising CFD results for S&C applications
- Geometry/grid generation for complex configuration is still the most time consuming part of the process ~ major improvements & automation needed
- Turbulence models inadequate for separated flow simulation ~ require continuous improvements
- Solvers robustness/efficiency need improvements for complex flow simulations encountered in S&C applications

Acknowledgements

- Boeing Commercial Airplanes
  - ~ CFD application group
  - ~ Product development : S&C, Loads groups
  - ~ Product support group

- NASA Langley/Ames Research Centers
  - ~ TLNS3D, CFL3D support
  - ~ OVERFLOW support